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The New PRIUS Powertrain : The New 1.8L ESTEC 2ZR-FXE Engine with the New Generation Hybrid System

Der neue PRIUS Antriebsstrang : Der neue 1.8L ESTEC 2ZR-FXE Motor mit dem neuen Hybridsystem

Abstract

The New PRIUS Powertrain has adopted the new 1.8L ESTEC 2ZR-FXE engine with the new generation hybrid system.
The new 4-cylinder engine achieves a high maximum thermal efficiency of 40% which is the world's highest for a mass-produced gasoline engine.
Obtaining a high engine thermal efficiency is of high importance for achieving customer's satisfaction. Toyota Motor Corporation has started developing a series of engines which belong to its new development concept called Economy with Superior Thermal Efficient Combustion (ESTEC). Toyota has been developing fast combustion technologies to enhance the engine thermal efficiency for conventional vehicles and hybrid vehicles (HVs). Similar to other ESTEC engines, the new 2ZR-FXE engine utilises a large amount of exhaust gas recirculation (EGR) gas with uniform distribution by the new shape intake manifold to achieve a thermal efficiency of 40%. In addition, knock resistance has been improved and mechanical loss has been reduced by various component e.g. the new shape crank bearing.
The new generation Toyota hybrid system is completely re-engineered to maximize the potential of THS (Toyota Hybrid System).

Kurzfassung

Der neue PRIUS Antriebsstrang verwendet den neuen 1.8L ESTEC 2ZR-FXE Motor in Verbindung mit dem neuen Hybridsystem.
Der neue 4-Zylindermotor erreicht einen hohen maximalen thermischen Wirkungsgrad von 40%, dem derzeit höchsten für einen Serienbenzinmotor.
Hoher thermischer Wirkungsgrad ist sehr wichtig, um Kundenzufriedenheit mit dem Produkt zu erreichen. Toyota Motor Corporation entwickelt eine Motorenreihe mit dem Konzept "Economy with Superior Thermal Efficient Combustion (ESTEC)". In diesem Rahmen legt Toyota besonderes Augenmerk auf Verbrennungstechnologie für einen hohen thermischen Wirkungsgrad für konventionelle Antriebe und Hybridfahrzeuge (HVs). Wie andere ESTEC Motoren nutzt der neue 2ZR-FXE Motor eine grosse Menge Abgasrückführung (EGR) mit gleichförmiger Verteilung in dem neugestalteten Ansaugkrümmer. Zudem wurde die Klopfbeständigkeit verbessert und die Reibung durch Optimierung verschiedener Komponenten, z.B. dem unteren Pleuellager, reduziert.
Die neue Generation des Toyota Hybridsystems ist komplett überarbeitet, um das Potential des THS (Toyota Hybrid System) zu maximieren.

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1. Introduction

Toyota launched the world's first mass-produced hybrid vehicle PRIUS in December 1997 and in July 2015, Toyota achieved 8 million total unit sales (Fig. 1).
Toyota announced CO2 reduced by hybrid vehicles reached approximately 58 million tons by July 2015 comparing to equal class vehicles in size and power performance. Toyota also calculated reduced amount of gasoline usage is about 22 million liters.

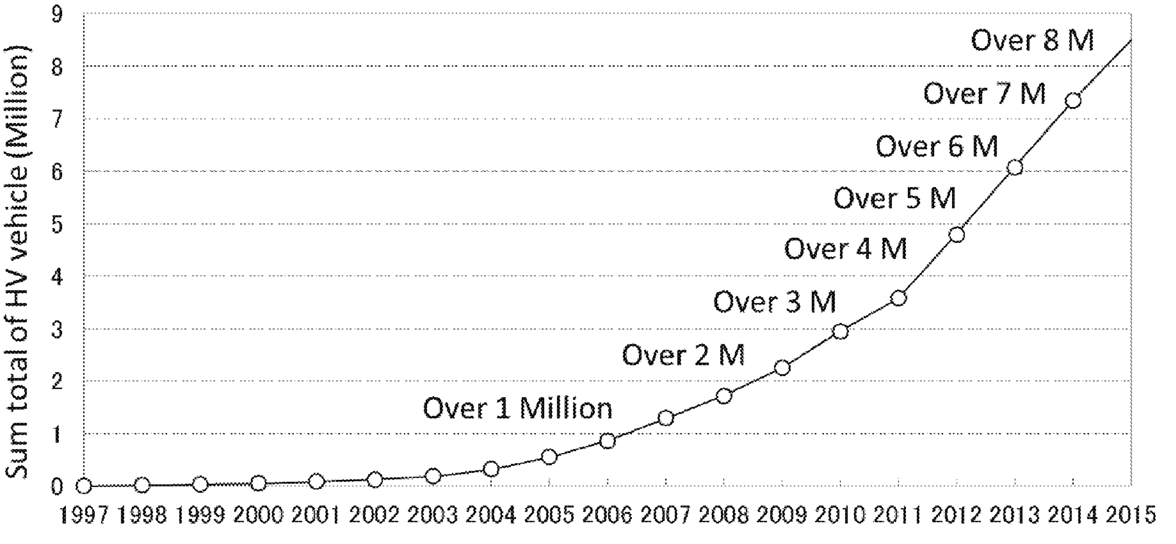

Figure 1 Cumulated Toyota vehicle sales with THS technology over years

The new 2ZR-FXE was refined along with ESTEC (Economy with Superior Thermal Efficient Combustion) development concept to achieve the thermal efficiency of 40% which is the first and best in mass-produced gasoline engines. This paper describes fuel efficiency improvement technologies adopted in the new ESTEC 2ZR-FXE engine.

2. Improvement concept

Fig. 2 shows the relationship between the engine thermal efficiency at various operating points and the usage distribution of previous PRIUS (HV). A hybrid vehicle has an EV (electric vehicle) function to run the engine under the high thermal efficiency area. This operation gives HVs a fuel efficiency advantage over conventional vehicles and shows the importance of enhancing maximum thermal efficiency for the development path of Hybrid engines.
The new ESTEC 2ZR-FXE engine incorporates various technologies to improve combustion characteristics, knocking, heat management, and mechanical loss for further enhancement of fuel efficiency. As a result, this new highly fuel efficient engine is now the first gasoline engine in the world to achieve a maximum thermal efficiency of 40% (Fig. 3). Fig. 4 and Table 1 show a view of the new 2ZR-FXE engine and its main specifications respectively.

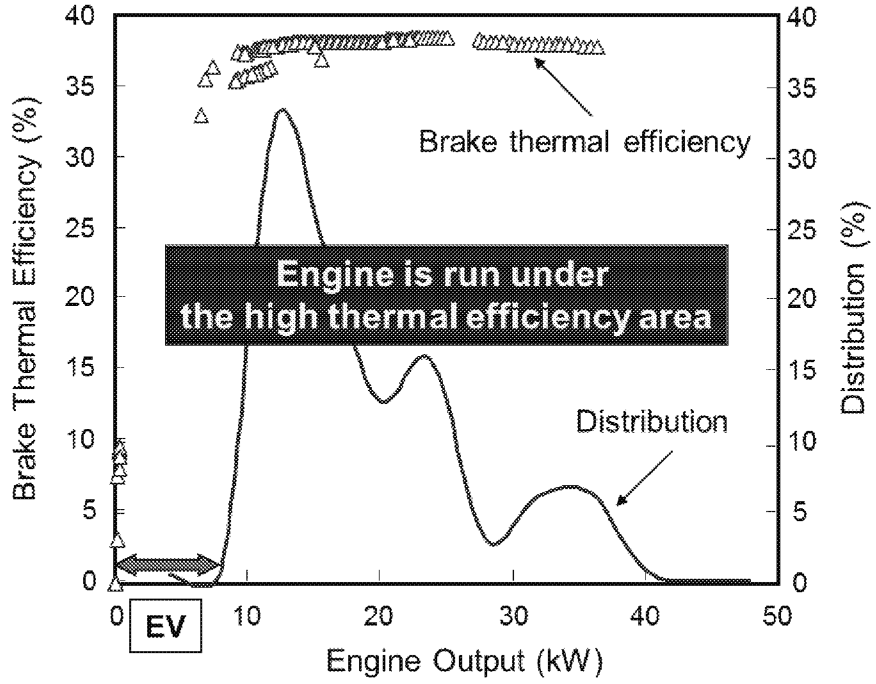

Figure 2 Relationship between the engine thermal efficiency at various operating points and the usage distribution of previous PRIUS

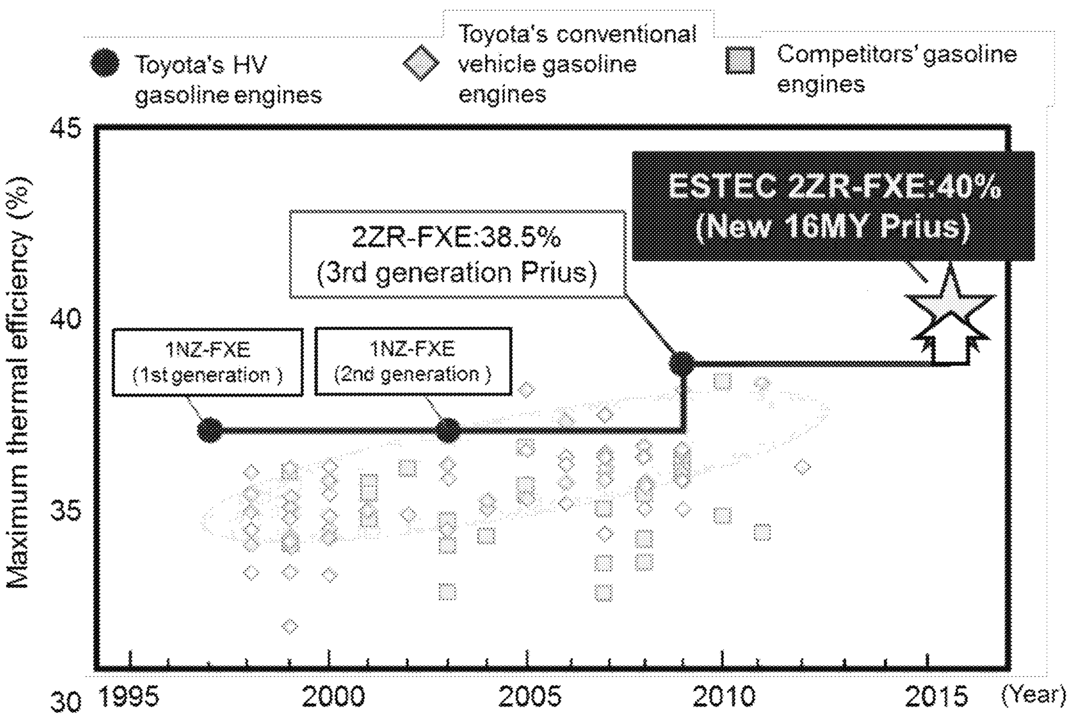

Figure 3 Development of gasoline engine thermal efficiency over years

Figure 4 ESTEC 2ZR-FXE engine

Table 1 ESTEC 2ZR-FXE Engine Specifications

Engine			ESTEC 2ZR-FXE
Displacement / Engine Type		(cm^3)	*1798 / Inline 4*
Bore × Stroke		(mm × mm)	*Φ80.5×88.3*
Compression Ratio			*13*
Fuel			*95 RON*
Fuel Injection System			*Port Injection*
Valve Train	Intake / Exhaust		*VVT-i / —*
EGR			*Cooled EGR*
WOT Performance	Max. Power	(kW / rpm)	*71 / 5200*
	Max. Torque	(Nm / rpm)	*142 / 4000*
Maximum thermal efficiency		(%)	*40*

3. Technologies to Enhance Fuel Efficiency

3-1. Improving Combustion Characteristics and Knocking

Cooled EGR is widely known as a technology to reduce knock and pumping loss. As shown in Fig. 5, at high-load condition, knocking decreases the brake thermal efficiency. The new ESTEC 2ZR-FXE has been developed to utilize cooled EGR ratio.

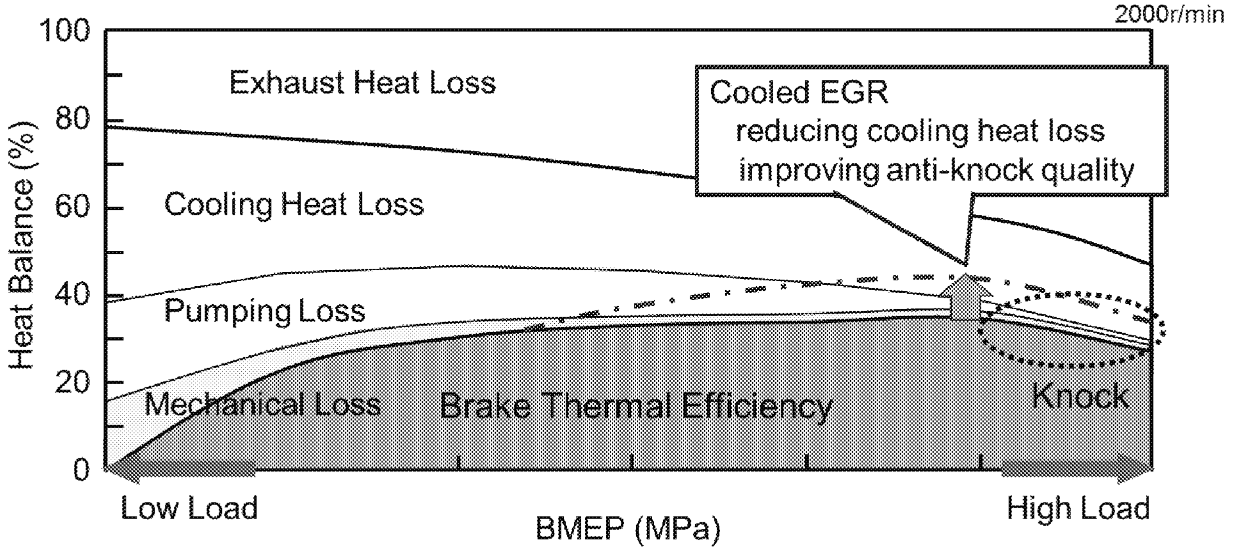

Figure 5 Effect of Cooled EGR on heat balance

3-1-1. High-Speed Combustion

High-speed combustion is an effective way for expanding EGR limit. This can be realized by intensification of in-cylinder turbulent flow fields (high tumble ratio).

In the new engine, the intake port specification was optimized to achieve a straight air flow in the tumble direction and to reduce a reverse tumble air flow within the cylinder. As a result, tumble ratio was increased from 0.8 to 2.8 (Fig. 6).

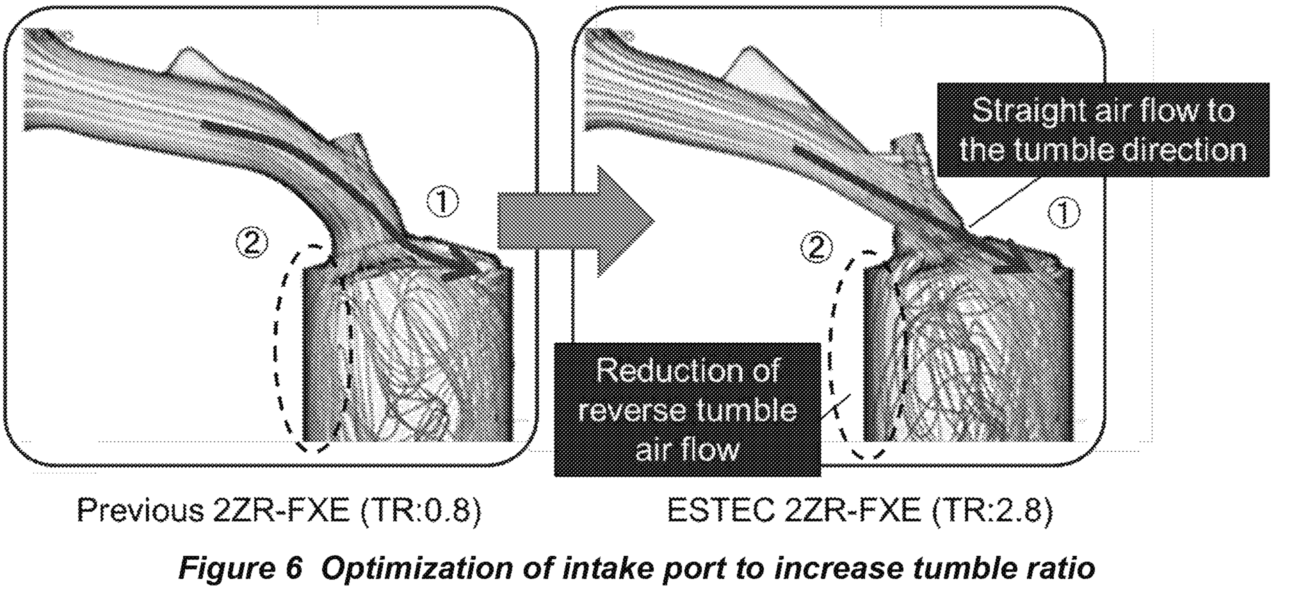

Figure 6 Optimization of intake port to increase tumble ratio

To increase the turbulence intensity of the mean air, the effect of piston shape has to be also taken into consideration. Fig. 7 and Fig. 8 show 3D drawing of two different piston shape design and their corresponding effect on mean air turbulence intensity respectively. As shown in Fig 8, higher turbulent intensity was achieved using design no 2.

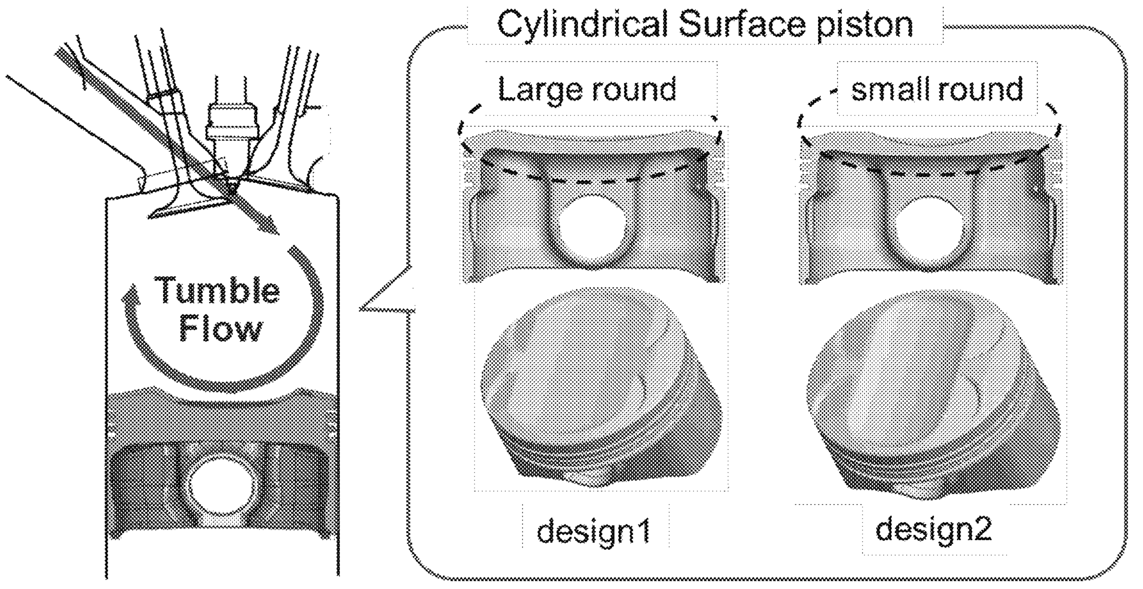

Figure 7 Piston design

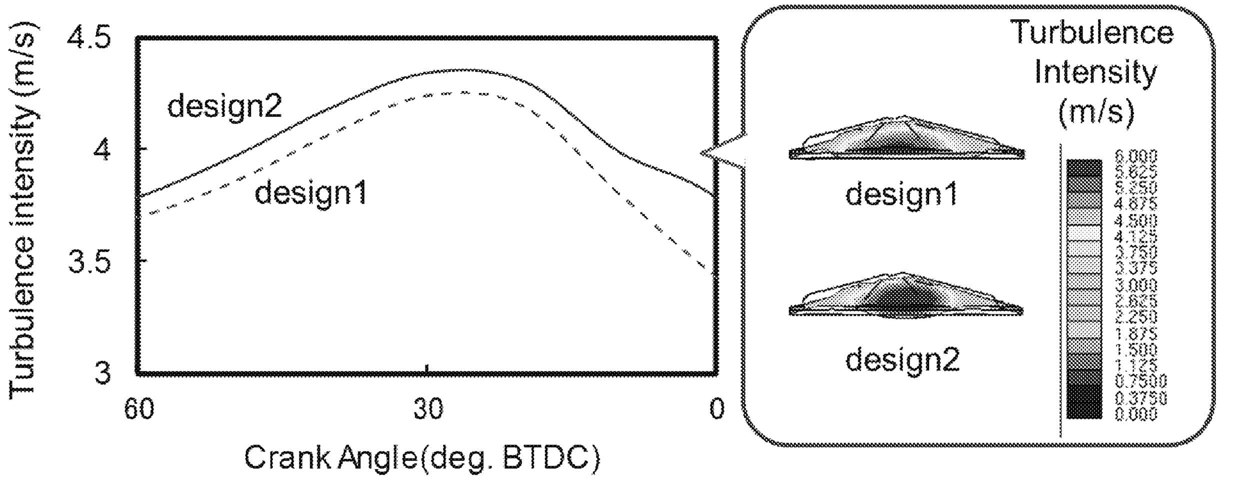

Figure 8 CFD result of mean air turbulence intensity in compression stroke

Enlarging the ignition source into a parabola is an effective way to form a large flame kernel. Fig. 9 shows CFD result of air flow velocity in the vicinity of the spark plug during the compression stroke. As it can be seen in this figure, the air velocity within the combustion chamber of ESTEC 2ZR-FXE engine is increased significantly comparing to its predecessor. The effect of higher air flow at TDC on stretching arc discharge can be seen in Fig 10.

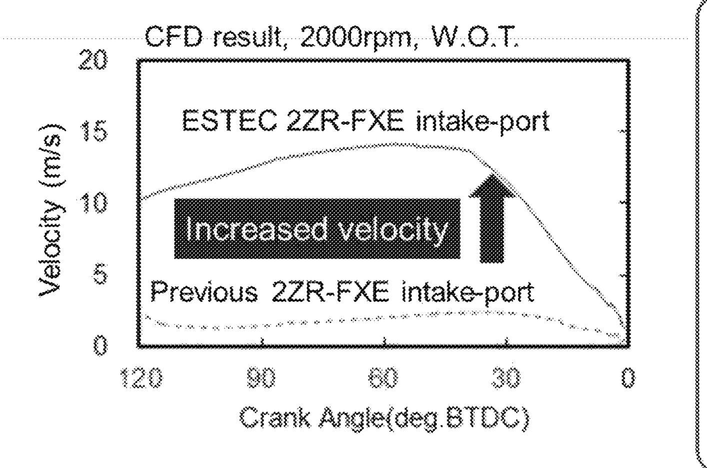

Figure 9 CFD result of air flow velocity in the vicinity of the spark plug

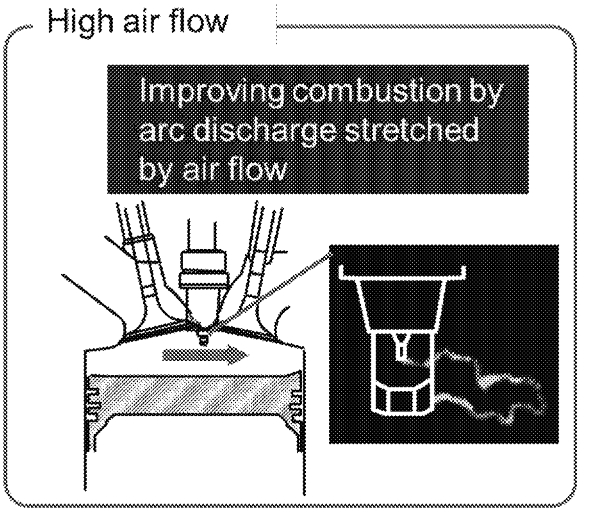

Figure 10 Spark stretch by air flow

3-1-2. EGR Distribution to Each Cylinder

To achieve the highest EGR ratio in each cylinder and to reduce the variation of EGR distribution between cylinders to less than 1%, the shape of intake manifold was tuned accordingly.
By CFD analysis, EGR gas ratio of each cylinder was equalized by tuning EGR gas passage. Fig. 11 and Fig. 12 show the result of intake manifold study.

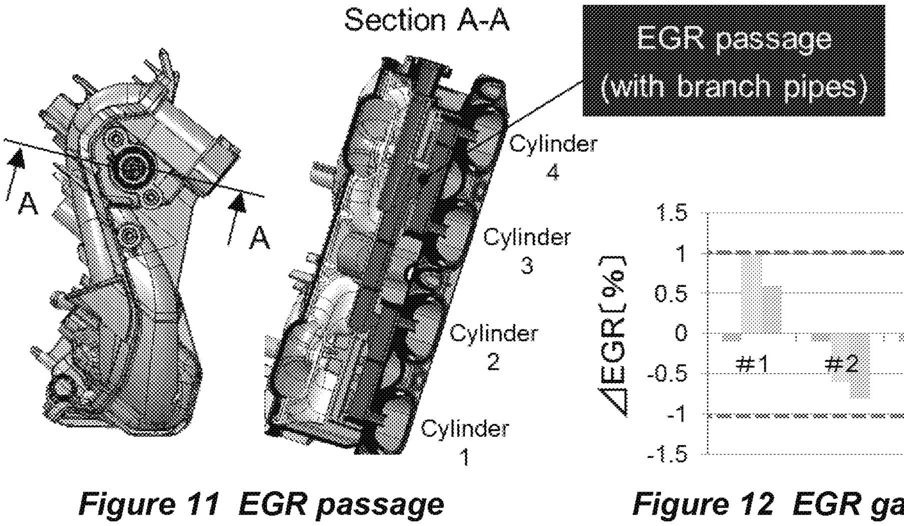

Figure 11 EGR passage

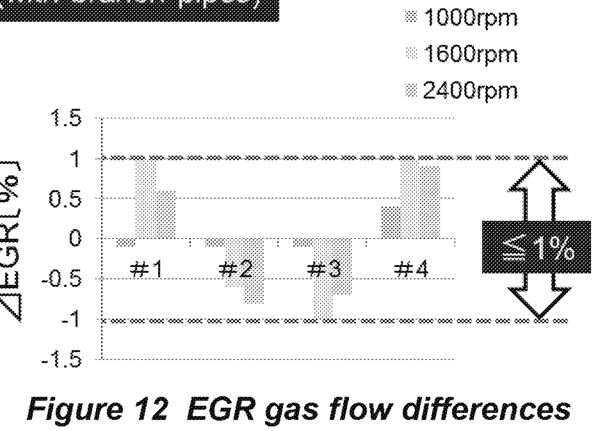

Figure 12 EGR gas flow differences

Through optimization of the intake port shape and piston shape, the duration of 10-90% combustion was shortened by 35% (Fig. 13). This high-speed combustion leads to a strong combustion, and then EGR limit can be increased as shown in Fig. 14. Considering the combustion stability, EGR ratio was increased from 15% to 25%.

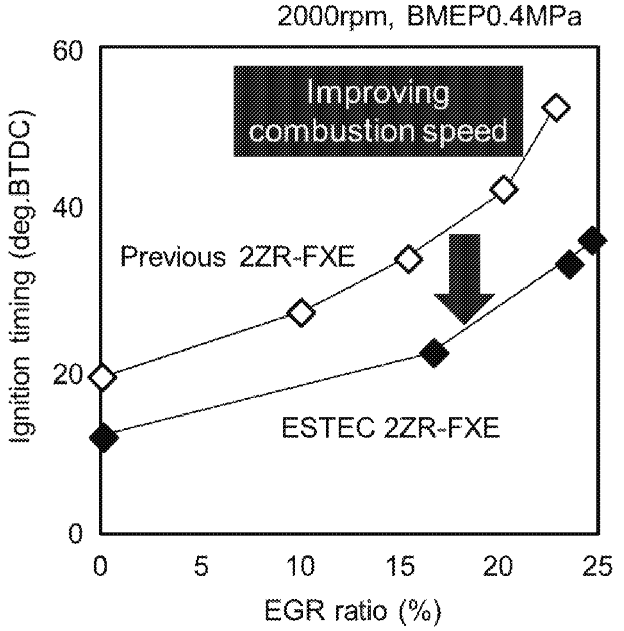

Figure 13 Improving combustion speed

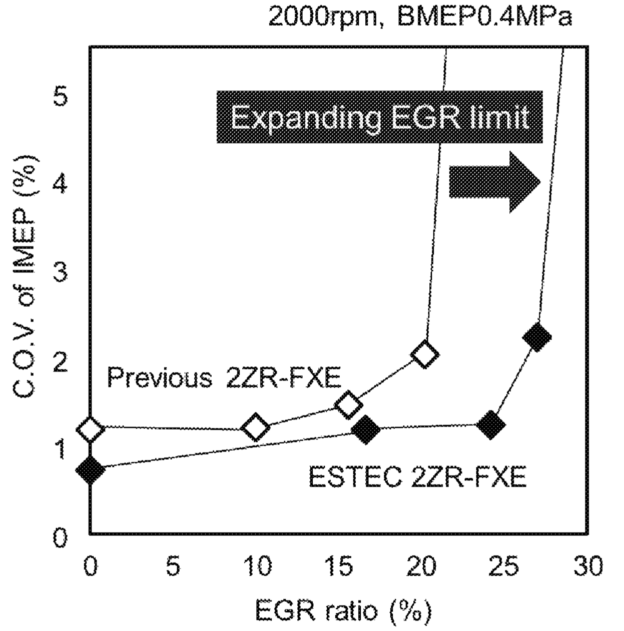

Figure 14 Expanding EGR limit

Fig. 15 shows the improvement of ESTEC 2ZR-FXE heat balance compared with its predecessor. The cooling heat loss of ESTEC 2ZR-FXE engine is reduced by 8% by extending EGR limit which consequently lowers the combustion temperature.

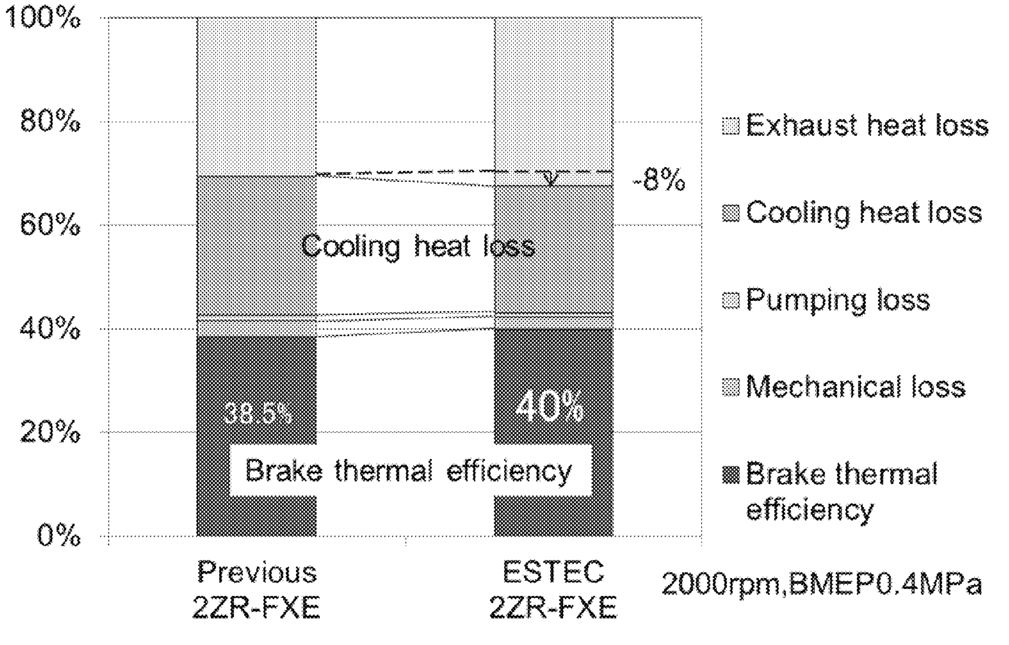

Figure 15 ESTEC 2ZR-FXE Heat balance & Break thermal efficiency

3-1-3. Stability of the Combustion

As mentioned in section 3-1-1, stretching spark plasma out from the plug electrodes improves the combustion process. However, blowout of the arc discharge is an issue in the case of strong flow fields.

Fig. 16 shows the relationship between the ignition energy and combustion duration. Under high EGR ratio of 25% and ignition energy of 100mJ, cyclic variation of combustion duration is reduced and misfiring cycles were improved. The high-energy ignition of 100mJ was adopted to stabilize the combustion process in ESTEC 2ZR-FXE engine.

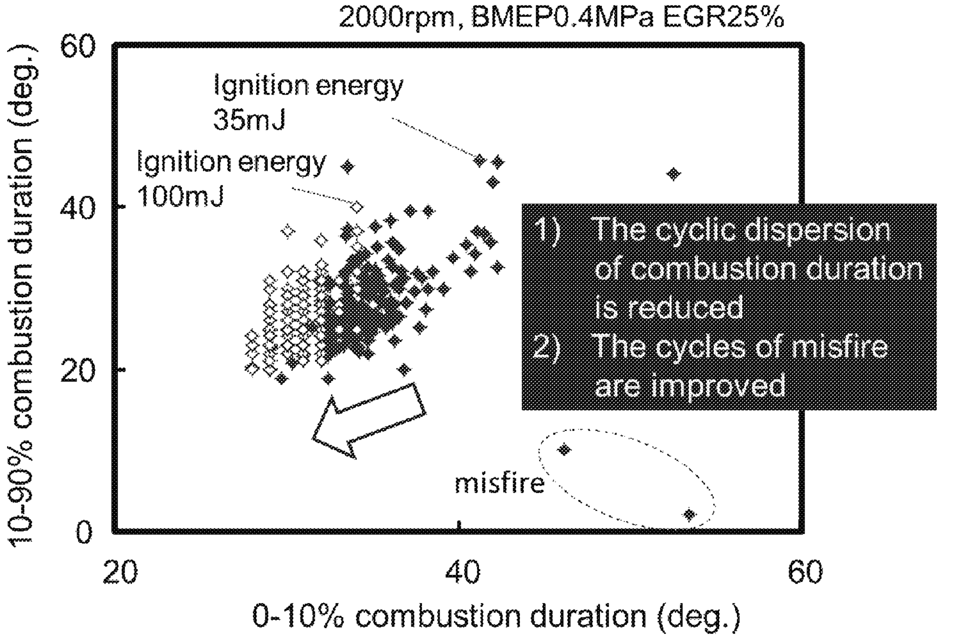

Figure 16 Relationship between ignition energy and combustion duration

The alignment of the spark plug grounding electrode was also optimized (Fig. 17). This alignment was done by controlling the starting positions of the male thread of spark plug and the female thread of cylinder head.

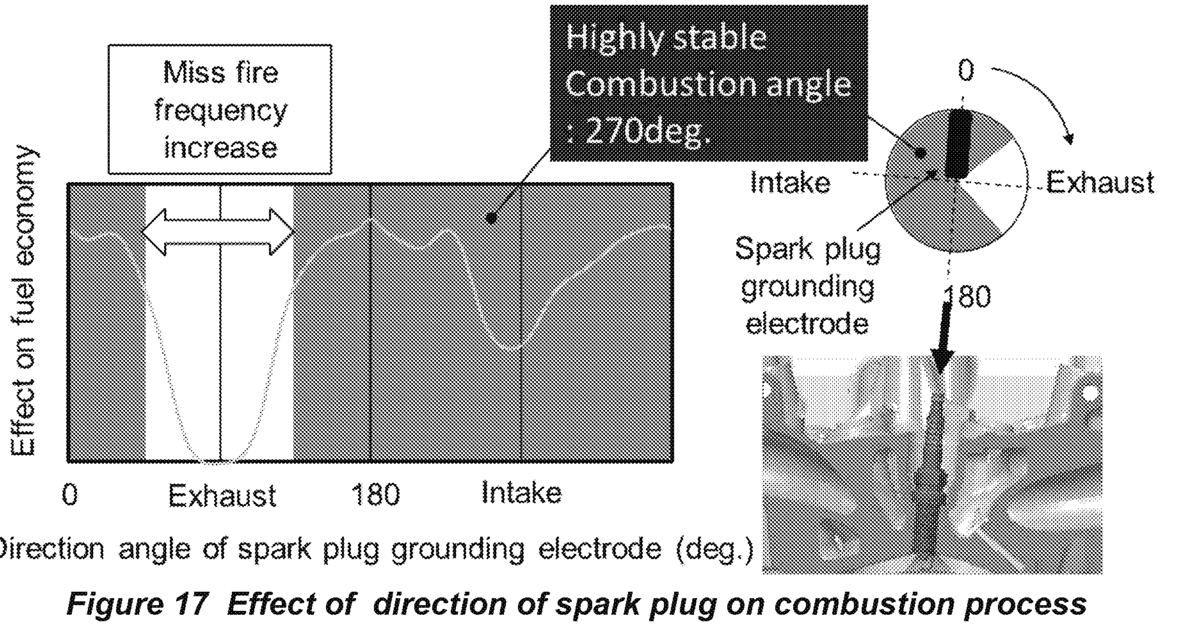

Figure 17 Effect of direction of spark plug on combustion process

3-1-4. Improvement of Scavenging Effect

To improve knocking resistance, it is important to lower the temperature of intake gas. To achieve this, ESTEC 2ZR-FXE valve overlap is designed as short as possible. Furthermore, the exhaust valve opening duration were extended which can reduce knocking by decreasing the exhaust pumping loss and increasing the scavenging effect (Fig. 18).

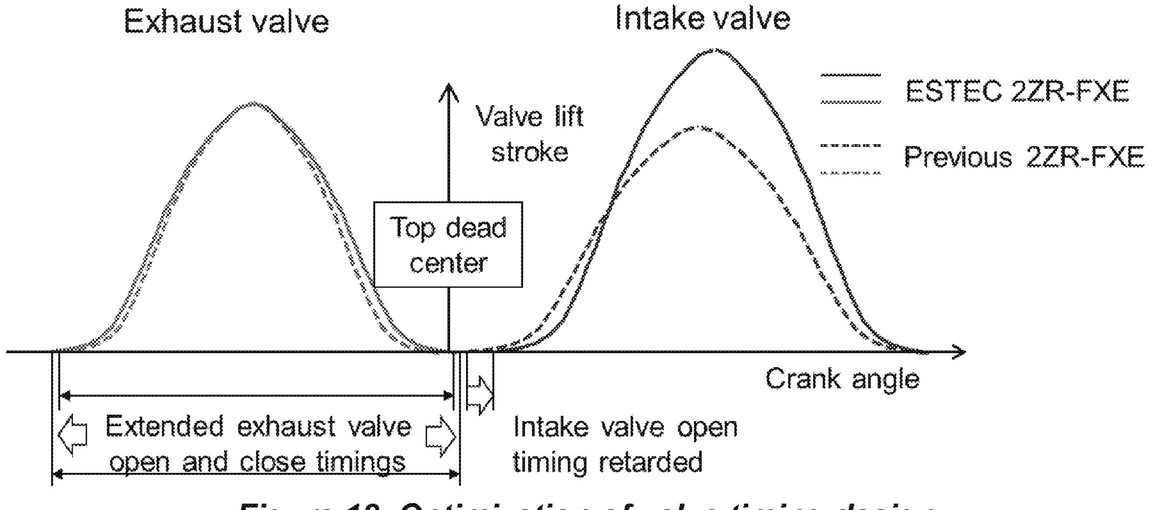

Figure 18 Optimization of valve timing design

Scavenging performance was enhanced by optimizing the length of exhaust manifold which consequently reduced the amount of residual gases and knocking. At the same time, moving the catalyst closer to the engine improved cold start catalytic performance (Fig. 19).

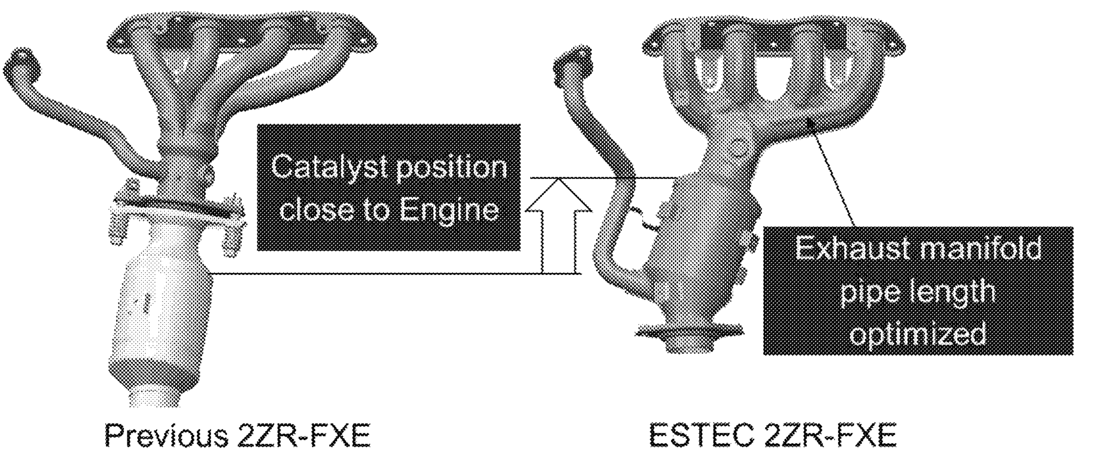

Figure 19 Optimization of exhaust manifold design

3-2. Heat Management

The engine heat management technology is important to enhance the thermal efficiency, to increase the knocking tolerance, and to reduce mechanical loss. In this regard, the heat management technologies, e.g. improving the cooling performance around the combustion chambers, were adopted in the new engine.

3-2-1. Water Jacket Spacer with EXPAD Foam Rubber Design

A water jacket spacer (WJS) with EXPAD foam rubber was placed in the cylinder block water jacket to optimize cylinder bore temperature distribution. The WJS consists of EXPAD foam rubber attached to a plate which controls the flow (Fig. 20). This component prevents knocking by cooling the upper range of the exhaust side of cylinder bore. This is the most effective means to cool the tumble flows. In addition, EXPAD foam rubber helps to reduce mechanical loss by maintaining the temperature of the center and lower area of the cylinder bore (Fig. 20).

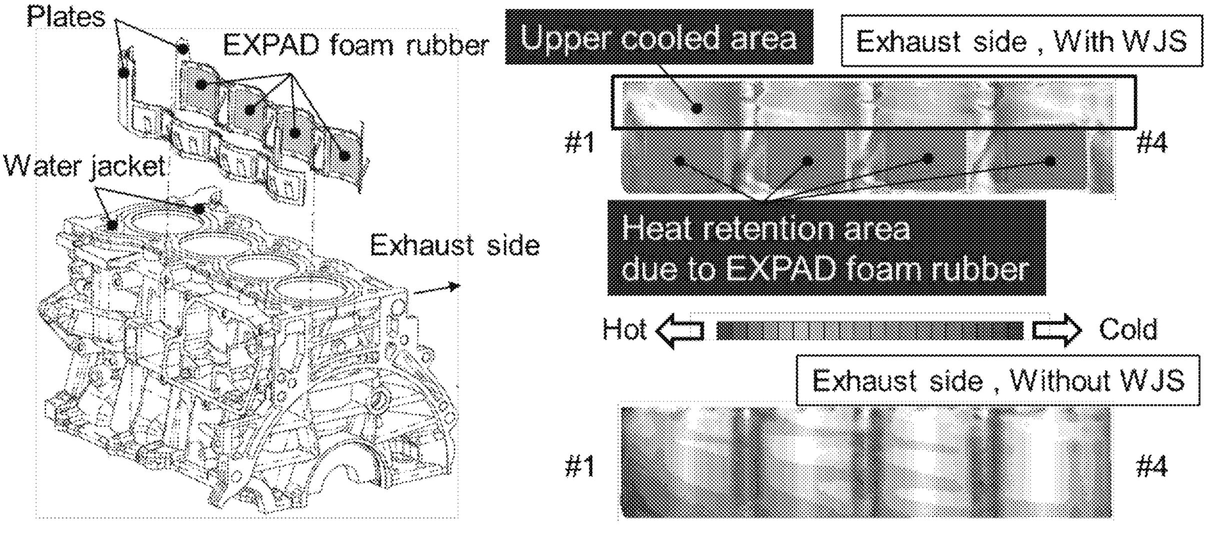

Figure 20 Effect of WJS with EXPAD

3-2-2. Cylinder Head and Cylinder Block Design

Improvements were added to reduce the water jacket pressure loss in the cylinder head for gaining the maximum cooling effect within the capacity of the electric water pump. In addition, cooling performance was improved by adding V-shaped drilled paths between the bores of cylinder block (Fig. 21).

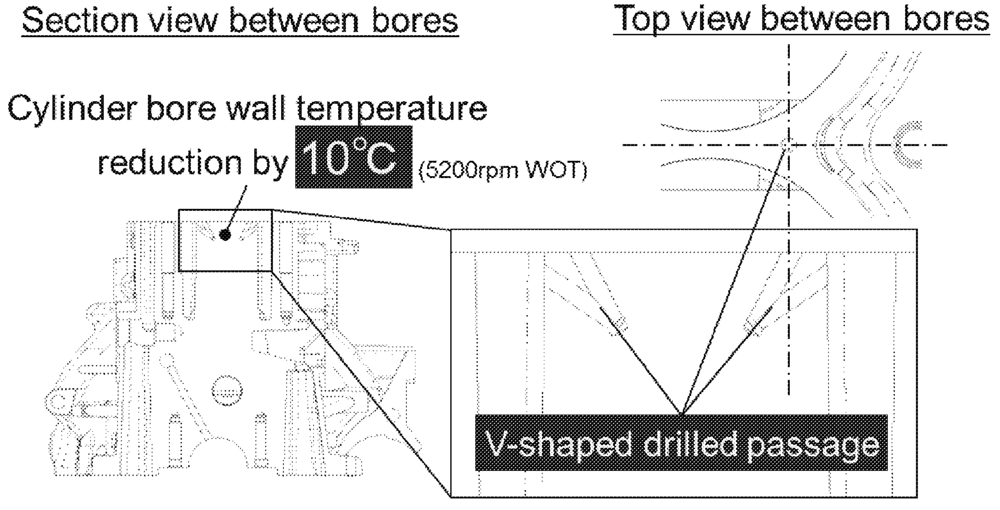

Figure 21 Improvement of cylinder block cooling

3-3. Mechanical Loss Reduction

Various measures were implemented to reduce mechanical losses and weight. In this regard, crankshaft bearings were improved by adding fine grooves. Fig. 22 shows the mechanism of reducing mechanical losses. The fine grooves generate negative pressure which draws oil into the grooves (1). This finally rises the temperature of the oil (2) and reduces mechanical losses by 15% (Fig. 23).

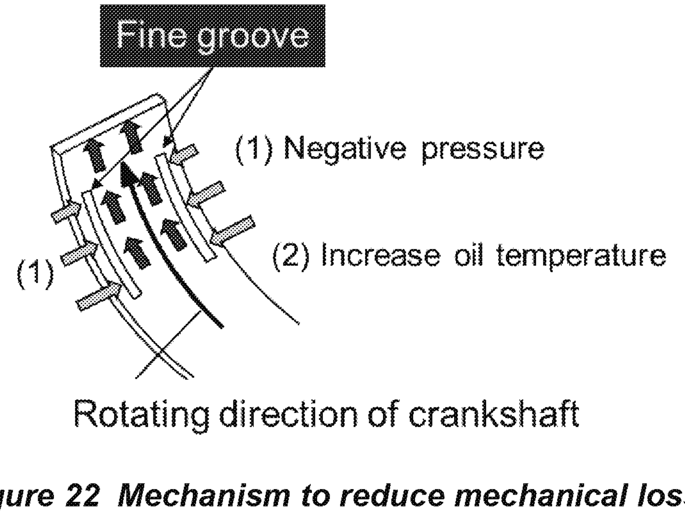

Figure 22 Mechanism to reduce mechanical loss

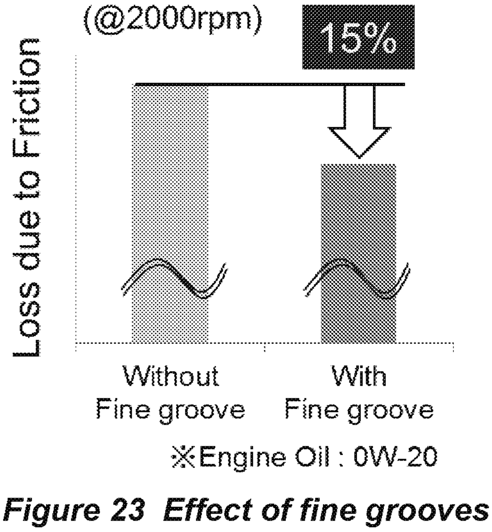

Figure 23 Effect of fine grooves

The inertial mass and load of the valve train were reduced by adopting narrower roller arms, compact retainers, and beehive-shaped valve springs.

In addition, oil pump with new rotor profile, narrow connecting rod bearings, low friction resin coated piston skirt, low friction chain with reduced sliding area were adopted. As a result of these changes, the mechanical losses are reduced by 13.8% from the previous 2ZR-FXE (Fig. 24).

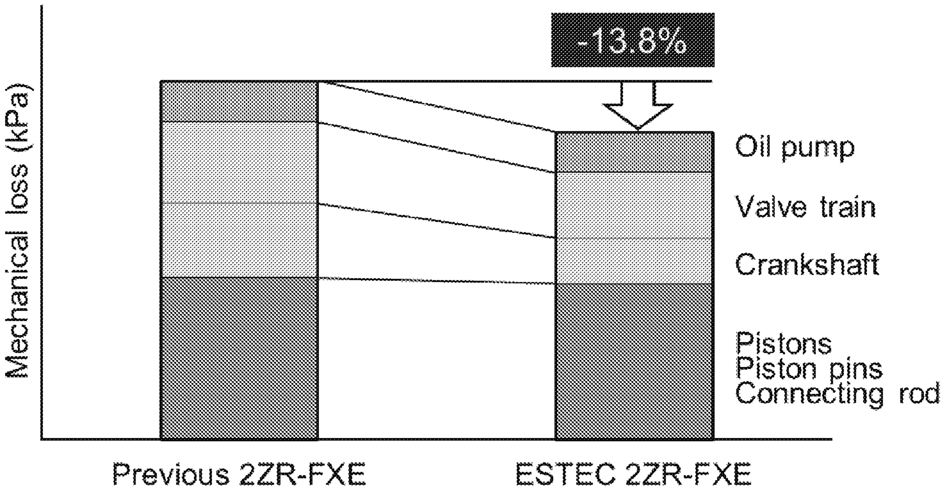

Figure 24 ESTEC 2ZR-FXE Mechanical loss

4. Vehicle Performance by New Generation Hybrid System

The previous hybrid system which was installed in 3rd generation PRIUS had a target to improve the high speed and cold condition's fuel economy. The development target of new 4th generation PRIUS is to maximize the potential of THS by re-designing all hybrid units to improve the fuel economy. Mechanical and electrical losses are reduced for the transaxle, motor, and PCU (Power Control Unit.). Also, the hybrid system including battery and software are re-designed to maximize each unit's performance.

4-1. Fuel Economy

Table 2 shows the fuel economy label of Japan, EU, and USA versions. Fuel economy has been improved by 25%, 21%, and 12% over the previous model respectively.

Table 2 Fuel Economy Label

Dest.	Driving Mode	New	Previous
Japan	JC08(km/L)	40.8	32.4
EU	NEDC(gCO2/km)	70	89
USA	Combined(mpg)	56	50

Fig. 25 shows the contribution rate of each component for fuel economy improvement in Japanese standard driving mode JC08, and Engine is the biggest contributor.

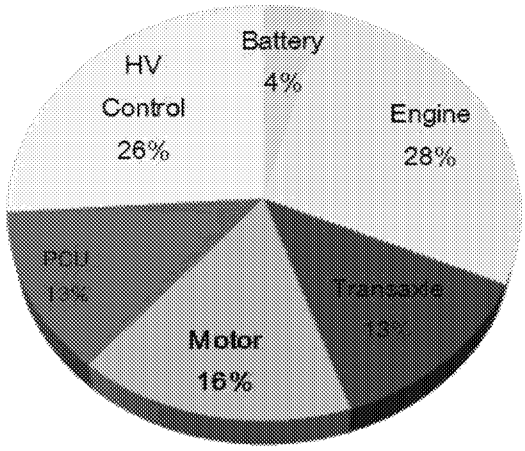

Figure 25 Contribution Rate for Fuel Economy

Fig. 26 shows engine thermal efficiency and difference of engine operating time distribution in US06 mode between previous and new system. Since the maximum vehicle speed for intermittent engine stop has been increased up to 110km/h, the new system is able to utilize higher thermal efficiency zone especially during high speed driving. (Fig. 27)

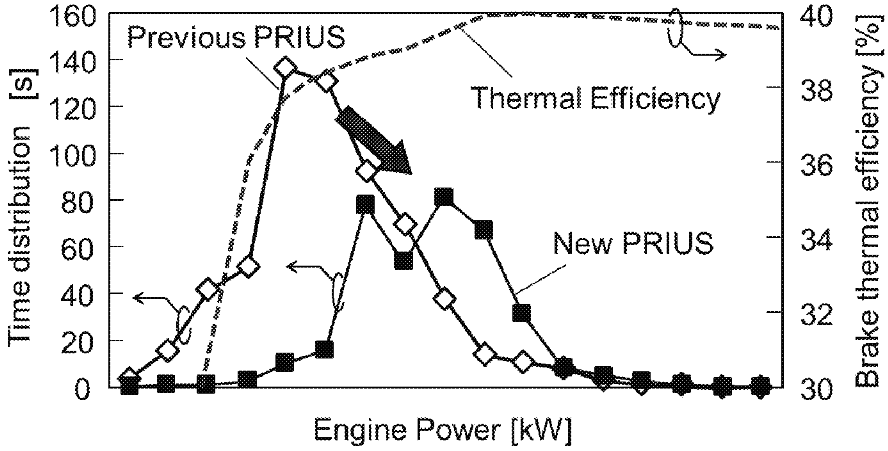

Figure 26 Comparison of Thermal efficiency usage of US06 mode

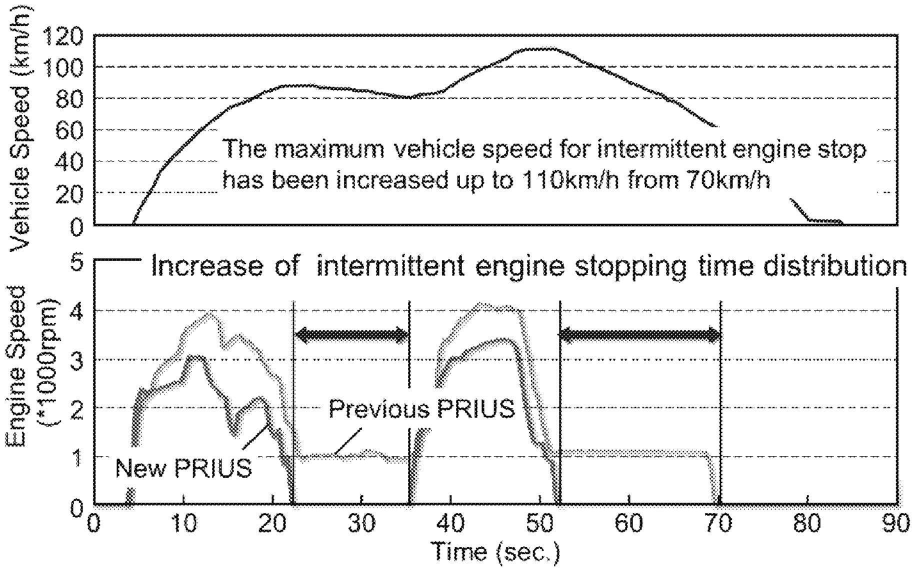

Figure 27 Intermittent engine stop during high speed driving

5. Conclusion

- Toyota developed the new 1.8L ESTEC 2ZR-FXE engine and the new generation hybrid system for the New PRIUS Powertrain.
- This new ESTEC 2ZR-FXE engine achieved an innovative thermal efficiency of 40%. It is the first and the best in the mass-produced gasoline engines.
- Combustion characteristics and knock resistance of ESTEC 2ZR-FXE were improved by high-speed combustion technology, good EGR distribution to each cylinder, good stability of the combustion and increasing scavenging effect.
- ESTEC 2ZR-FXE reduced the mechanical loss by 13.8% from previous 2ZR-FXE.
- New generation hybrid system improved fuel economy performance in Japan:25%, EU:21%, and USA:12% over the previous vehicle respectively by optimizing the engine efficiency zone usage.

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